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Abstract

The National Ignition Campaign has the goal of developing a robust burning plasma platform which will produce up to $\sim 10^{19}$ neutrons in ~ 20 psec. To measure the temporal history on the burn time scale will require diagnostics that possess a time resolution of a few ps and the ability to function in an environment containing an extremely large neutron flux. One solution to this challenge is to perform an ultrafast conversion of the x-ray signals into the optical regime. A diagnostic based upon these principles has been developed using a linearly chirped probe beam to measure the temporal history of the x-ray pulse. This diagnostic technique was tested on a laser-produced x-ray source and obtained a measurement of the full-width-at-half-maximum of the x-ray pulse of <10 ps.

The National Ignition Campaign, NIC, has the goal of developing a robust burning plasma platform with projected neutron yields approaching 10^{19} neutrons produced in a time of 15 – 20 psec. The very short duration of the burning plasma means that fast time resolution of a few ps will be required for ignited plasma research. These instruments must function in an environment containing an extremely large neutron flux which will cause conventional diagnostics to fail due to radiation damage and induced background levels.[1] One solution to measuring x-ray signals with ps resolution in such an environment, approaching 10^{19} neutrons, is to perform an ultrafast conversion of the x-ray signals into the optical regime, <100 fs, before the neutrons are able to reach the detector. The signal can then be relay imaged out of the chamber and into a shielded bunker, protected from the effects of these neutrons. In this article we present results from an x-ray diagnostic that utilized this approach and which was tested using a laser-plasma x-ray source. This diagnostic is an extension of work that has been performed with an optical pump in the laboratory to demonstrate an imaging diagnostic.[2] Alternative approaches to performing an ultrafast conversion of the x-ray signals into the optical regime by using semiconductors in conjunction with a Fabry-Perot cavity have also been developed.[3,4]

The principle of the detection concept discussed in this article uses the free carrier induced phase shift in the index of refraction of a semiconductor when it is exposed to x-rays or any photons with an energy greater than the semiconductor's bandgap energy. This phase shift is largest near its bandgap and causes a local phase shift which is proportional to the x-ray fluence. This then enables imaging of the two-dimensional x-ray fluence on the semiconductor by measuring the two-dimensional phase profile in the semiconductor induced by the x-ray fluence. The technique used to measure this phase shift incorporates a binary x-ray grating mask to spatially modulate the x-ray flux incident on the semiconductor. The spatially modulated x-ray flux writes a transient carrier-induced phase grating in the semiconductor, which persists for a time duration ranging from several ps to several ns. The radiation induced grating diffracts signal images at an angle relative to the probe beam during the time it exists. The diffracted signal is spatially separated from the zero order probe beam in the Fourier plane, far-field, where it can be easily detected. To achieve a continuous time readout of the x-ray flux, a linearly frequency chirped and temporally stretched probe beam tuned below the band edge of the semiconductor is incident upon the semiconductor. Each frequency in the probe beam is incident upon the semiconductor at a different time, which enables the temporal history of the x-ray flux to be associated with the frequency spectrum of the probe beam. A grating is then used to disperse the linearly chirped light from the semiconductor, zero order and diffracted orders, across a CCD detector thereby creating a time record of the phase shift in the semiconductor due to the x-ray flux incident upon the semiconductor. A schematic of this process is shown in Figure 1.

The experiments conducted to test this x-ray detector were carried out on the Jupiter Laser Facility at the Lawrence Livermore National Laboratory and in particular on the Callisto Ti:Sapphire laser. The x-ray source was produced by focusing the 60 fs Ti:Sapphire laser, centered at 805 nm, onto a 100 um thick Titanium foil. The laser energy was varied between 0.1 and 5 J for the various shots. The laser was incident on the target at an angle of +35 degrees from normal with p polarization and the spot size was measured to be less than 20 microns in diameter with intensities greater than 10^{19} W/cm^2 on the highest energy shots. This produced an x-ray source dominated by the Titanium 4.5 keV K_α x rays as determined from the spectra obtained with a single hit x-ray CCD camera. The CdSe detector was placed 15 mm away from focus at ~ -40 deg from target normal. The x-ray fluence was measured with an x-ray pin diode from

International Radiation Detectors Inc., AXUV100GX, that was filtered with the same filter as the CdSe and located ~ +45 degrees from target normal. Several calibration shots were taken with an x-ray pin diode in the location of the CdSe detector, -40 deg, in addition to the 45 deg. location to account for the angular dependance of the x-ray fluence.

The experimental setup of the diagnostic is shown in Figure 2. A linearly chirped probe beam centered at 805 nm and with a FWHM bandwidth of 25 nm and a FWHM pulse length of 153 ps was passed through an apodizer and then relay imaged onto a CdSe detector. CdSe was chosen primarily due to the close proximity of its band gap energy, 1.74 eV, to the experimental facility's probe beam energy, 1.54 eV. The CdSe detector was AR coated for 805 nm on the side upon which the probe beam was incident. The side facing the impinging x rays was coated with 250 nm of copper to provide a reflective surface for the probe beam but to allow passage of the x rays through the copper reflector and into the CdSe semiconductor. An x-ray grating was placed in contact with the copper HR layer to provide the spatial modulation of the impinging x rays. The x-ray grating was constructed by Microworks Gmbh with an overall pitch of 20 um, 10 um wide and 10 um thick gold bars with 10 um wide and 16 um thick epoxy resin in between the gold bars.

X rays impinging upon the semiconductor are spatially modulated by the gold grating in contact with the CdSe detector. The x rays that get absorbed in the CdSe create electron-hole pairs which change the index of refraction of the CdSe thereby creating a phase grating within a few x-ray absorption lengths from the copper coated surface facing the plasma. The linearly chirped probe beam passes through this phase grating and is diffracted into the various orders of the grating. The diffracted light from the CdSe is relay imaged outside of the vacuum chamber and another lens is used to form the Fourier plane where the different orders of the induced phase grating are spatially separated. A half plane filter was then used to attenuate the zero order of the induced phase grating to bring the amplitude of the zero and first orders to a comparable level on the CCD camera to maximize the dynamic range of the measurement. A lens was then used to image the Fourier plane onto a CCD camera with a grating placed after the lens to disperse the linearly chirped probe beam across the CCD, in the orthogonal direction to the zero and first orders formed by the induced phase grating in the CdSe. This then provided the temporal measurement of the x-ray flux. The technique of using a chirped laser in combination with a grating has been used previously to make continuous time measurements of plasma densities[6] and has been proposed for framing and streak cameras diagnostics[7].

The persistence time of the imposed phase grating inside the semiconductor is semiconductor dependent and can be engineered by introducing trapping centers into the semiconductor either by impurities or by irradiating the semiconductor with high energy neutrons, electron or protons.[8,9] The CdSe semiconductors described in this article had recombination times much longer that the x-ray pulse originating from the laser-produced plasma. In that sense the semiconductor acted like an integrating detector in which the time-dependent x-ray signal was determined by differentiating the diffracted signal in time to determine the x-ray flux.

The raw data from one of the shots recorded on the CCD is shown in Figure 3. In this case the zero order, which was attenuated by a factor of 3,620 relative to the first order, is shown across the bottom of the figure where time is running from left to right. Both the absolute value of the time axis, 0.31 ps/pixel, and the direction was determined by placing a known delay in an optical trombone in the probe beam and taking the cross-correlation of the two first order diffracted signals to determine the offset in pixels between the two successive shots. This value was consistent with the value expected given the chirp parameter of the probe beam, the dispersion of the grating and distance between the grating and the CCD camera. In addition to the data shown in Figure 3, images were also recorded before and after the shot to enable the scattered light from the probe beam to be subtracted from the image.

Although the amplitude modulated x-ray grating was a binary grating with equal width bars and troughs, the induced phase grating inside the CdSe was not. This was apparent due to the presence of a second order component to the grating. By performing a sequence of wave-optics simulations of trapezoidal phase gratings[10] and comparing the ratio of energy in the first and second orders and in the first and third orders it was determined that a trapezoidal grating with a bar width normalized to the grating pitch of 0.14, a trough width normalized to the grating pitch of 0.36 and a linear transition region between the trough and bar normalized to the grating pitch of 0.25 gave the best fit to the measured data. These wave-optics simulations further determined that the energy in the first order, E_1, of the grating relative to the energy in the zero order, E_0, for such a grating shape could be expressed as $E_1/E_0 = 0.067(\phi)^2$, where ϕ is the phase amplitude of the grating in radians.

Given the expected dependence of the energy scattered in the first order of the grating relative to the zero order of the grating, the x-ray flux can then be analyzed by subtracting the normalized scattered light, dividing the first order scattered light by the energy in the zero order component and then taking the square root of this signal to determine the phase induced in the CdSe semiconductor and hence the cumulative integral of the x-ray flux impinging upon the semiconductor. This signal can then be differentiated to determine the x-ray flux. Before differentiating the signal the data was low pass filtered by Fourier transforming the 1-D data file, multiplying by a Blackman window and then inverse Fourier transforming the filtered signal.

The resulting data was then differentiated in time to arrive at the time-dependent x-ray flux shown in Figure 4. This data shows an x-ray pulse FWHM of <10 ps, much faster than obtainable with a PCD-oscilloscope combination which has 10% to 90% rise and fall times of 90 ps and 1.5 ns respectively.[11] The measurement as taken used a grating and the temporal resolution was limited due to the finite spot size on the CCD detector. Time resolutions of much less than 1 ps would readily be obtainable by either changing the chirp parameter of the probe beam or reducing the spot size such that the spectrometer dispersion multiplied by the spot size was smaller than the corresponding bandwidth of the desired temporal resolution. In the experimental setup the grating dispersion was 1.1 nm/mm, which for a 25 um slit width would have yielded a sub-ps response time. The double pass peak phase shift inside the CdSe was 0.11 rad as shown in Fig. 4. This phase shift indicates a response in the CdSe for the 805 nm probe beam of 0.11 rad/2./(3.2×10^{12} electron-hole pairs/mm^2) = 1.72×10^{-14} rad mm^2/electron-hole pair or 0.016 rad mm^2/uJ. This assumes a conversion factor of 5.3 eV required to create an electron-hole pair and also that the primary x-ray source was Ti k_α x rays. A single hit x-ray CCD camera was used to verify that the x-ray spectrum was indeed dominated by the Ti k_α and by a lesser extent the Ti k_β x rays.

In summary, a diagnostic capable of measuring the time-dependent x-ray flux has been built and tested with a laser-produced titanium plasma source The instrument measured an x-ray pulse width of <10 ps FWHM produced by a 60 fs high intensity laser focused on a Ti target. Sub-picosecond time resolution x-ray measurements are readily obtainable with this technique. This diagnostic utilized a CdSe semiconductor due to the proximity of the band gap energy, 1.74 eV(713 nm), to the probe beam wavelength of 805 nm. Large improvements in sensitivity could be realized by using an OPA to produce a wavelength significantly closer to the band gap energy and by cooling the sample to increase the change in the index of refraction within the semiconductor relative to the probe beam wavelength.[12] Sensitivity improvements can also be realized by choosing a semiconductor with less inherent internal scattering and better surface quality to reduce the level of scattered light, by choosing a semiconductor with a higher change in index of refraction per excited electron-hole pair, by decreasing the pitch of the spatially modulating x-ray grating thereby moving the diffracted signal to a region of lower scattered light, and also by using an interferometric detection scheme.[13]

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FIGURE CAPTIONS

Figure 1 X-ray detection scheme used to determine the time-dependent x-ray flux impinging upon the CdSe semiconductor.

Figure 2 Experimental geometry used to measure the x-ray flux produced by the laser-plasma source. Labels in the figure are: mirror(M), lens (L), beam splitter(BS) and half waveplate ($\lambda/2$).

Figure 3 Data recorded on the CCD showing the diffracted zero and first orders off of the semiconductor. The first order diffracted order turns on when the x rays from the laser plasma source pass through the x-ray grating, form electron-hole pairs inside the semiconductor and induce a phase grating on the inside of the semiconductor.

Figure 4 Time dependent double-pass phase amplitude, Φ, and its derivative, $d\Phi/dt$, driven in the CdSe by the spatially modulated x-ray pulse.

FIGURES

KL Baker

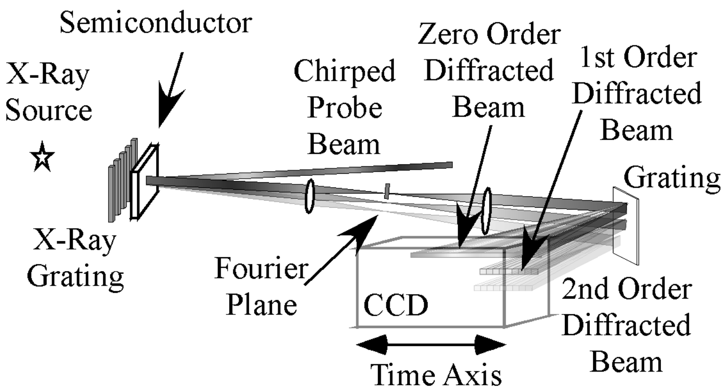
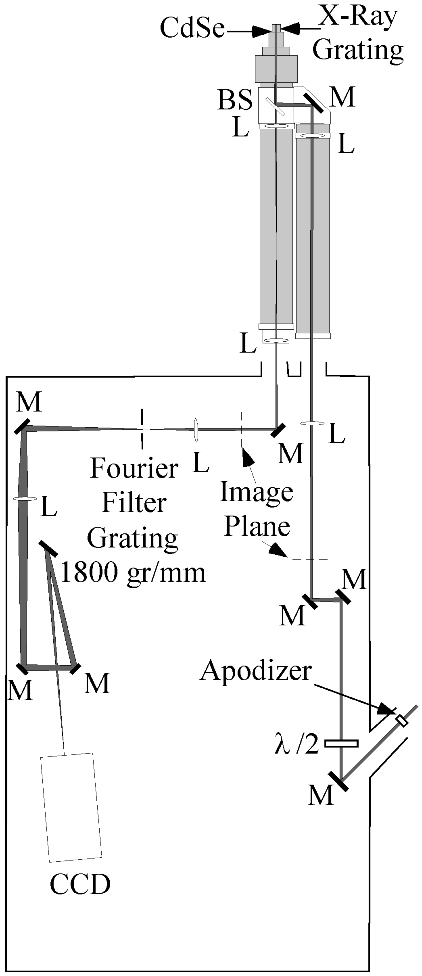


Figure 1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X-Ray
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Fourier
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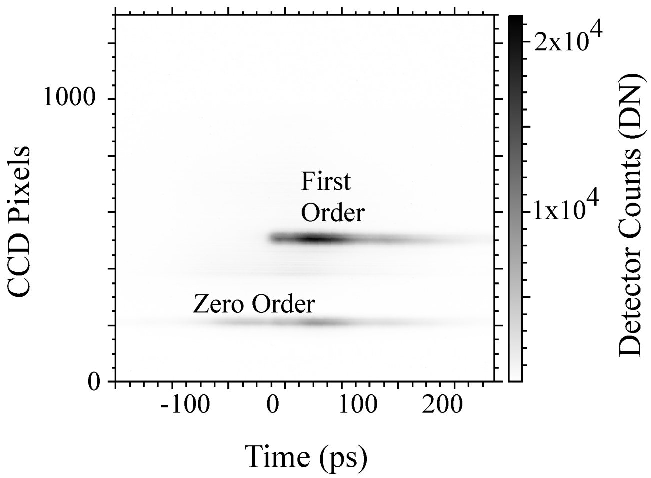
CCD

Figure 2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Detector Counts (DN)

Figure 3

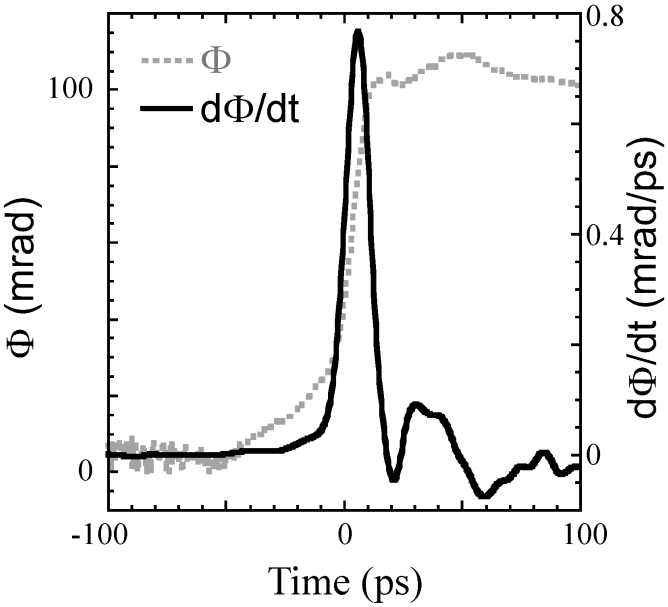

Figure 4